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WELDABILITY OF 2219-T851 AND 2519-T87 ALUMINUM ARMOR ALLOYS FOR USE IN ARMY VEHICLE SYSTEMS

THOMAS D. WOLFE and STEVEN A. GEDEON

PROCESSING TECHNOLOGY DIVISION

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ABSTRACT

A preliminary study of the weldability of 2219-T851 and 2519-T87 aluminum armor alloys was undertaken to determine the feasibility for their use in U.S. Army vehicle systems. Weldability was assessed in terms of weldment tensile strength, fatigue endurance limit, resistance to stress corrosion cracking, and ballistic shock integrity. Results show that 2519-T87 is a candidate material for replacing 5083-H131 or 7039-T64 due to high tensile strength and resistance to stress corrosion cracking.

The initial weldments failed ballistic qualification to MIL-STD-1946, but the results were encouraging. It is felt that, with recent joint design changes and alterations to the critical velocity requirements in MIL-STD-1946, 2519-T87 weldments can exhibit sufficient ballistic integrity.

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INTRODUCTION

This weldability study was initiated in support of the U.S. Army Materials Technology Laboratory's Laminate Armor Program (LAP).[1] Work began in 1984 at the request of the Program Manager, Mobile Protected Gun System (MPGS) at the Tank Automotive Command (TACOM). Rationale for the Laminate Armor Program was based on the concept of a light armored vehicle utilizing a welded aluminum plate hull/turret base structure, backed with aramid fiber-reinforced plastic to provide fragmentation and spall interior protection and faced with ultrahigh-strength steel plate appliques to defeat small caliber (up to 14.5 mm) armor piercing (AP) projectile threats.

Aluminum alloys have been the dominant structural material in light combat vehicles for the past 25 years. Welded aluminum plate hull and turret designs have dominated United States manufacturing technology for tracked armored personnel carriers, fighting vehicles, and self-propelled artillery pieces. Characteristics which make aluminum alloys desirable in this role include inherent ballistic resistance to kinetic energy projectiles, good strength-to-weight ratio, corrosion resistance, low material cost, and ease of fabrication (cutting, machining, and joining).

To date, only two alloys account for nearly all aluminum plate applications in combat vehicle structures: the strain-hardened 5083-H131 alloy conforming to MIL-A-46027, and the heat-treated higher strength (and higher cost) 7039-T64 alloy conforming to MIL-A-46063. Even though 7039-T64 has the higher strength, and thus improved ballistic protection, it has been plagued by susceptibility to stress corrosion cracking (SCC) in the through thickness short-transverse direction. Thus, 5083-H131 has been the most widely used aluminum alloy in light combat vehicles to date.

Introduction of the 2XXX series aluminum alloy 2519-T87 with tensile and ballistic properties equivalent to the 7039-T64 alloy provides, for the first time, a high strength, SCC resistant aluminum alloy for possible alternative vehicular structure applications. This is a recently developed alloy produced by Alcoa and developed in conjunction with FMC for use in combat vehicles. The 2219-T851 alloy conforming to MIL-A-46118 offers a SCC resistant aluminum alloy, but the tensile properties of this armor plate do not promise the ballistic resistance of either the 7039-T64 or 2519-T87. If either of these 2XXX series alloys are to be used on Army combat vehicles, they must demonstrate adequate weldability.

The purpose of this preliminary study is to evaluate the weldability of 2519-T87 and 2219-T851, as measured by the weldment's tensile strength, fatigue endurance limit, resistance to stress corrosion cracking, and ballistic performance. Primary emphasis was placed on 2519-T87 because of its promise to provide improved ballistic protection; thus the majority of experiments were on this alloy. Also, since 2519-T87 is such a new alloy, it was felt that a larger data base needed to be established for future Army needs. The results will be used in future studies to determine if these alloys can be used to replace or augment 5083-H131 or 7039-T64 on current or future Army light combat vehicles.

1. DeLUCA, E., and ANCTIL, A. *Laminate Armor for Light Combat Vehicles (U).* U.S. Army Materials Technology Laboratory, MTL TR 86-14, April 1986.

Also encompassed under the LAP study was the establishment of Military Standard MIL-STD-1946(MR) stating requirements for welding of aluminum armor including ballistic shock testing of welds, radiographic inspection, welder certification, and workmanship specimens. The Standard, when finalized, will replace the present armor welding document MIL-W-45206(MR). Specification MIL-A-46192 was also formulated under this study for the newly developed 2519-T87 (formerly Alcoa CW34) aluminum armor alloy.

EXPERIMENTAL PROCEDURES

All testing of weldments was conducted on specimens made from nominal 1-inch thick aluminum plate (except C-rings). Chemical composition of both 2219-T851 and 2519-T87 alloy plates are shown in Table 1. These aluminum-copper alloys obtain their high strength by a solution heat treatment and quench followed by strain hardening and artificial aging.

Table 1. CHEMICAL ANALYSIS OF THE 2XXX SERIES ALUMINUM ALLOYS TESTED (in weight percent)

Alloy/Form	Cu	Fe	Mg	Mn	Ni	Si	Ti	V	Zn	Zr
2219-T851/Plate	6.2	0.17	0.007	0.30	0.011	0.09	0.04	0.08	0.08	0.15
2519-T87/Plate	5.71	0.15	0.09	0.25	--	0.10	0.06	0.08	--	0.12
2319/Wire	5.8-6.8	0.30	0.02	0.20-0.40	--	0.20	0.10-0.20	0.05 0.15	0.10	0.10-0.25

Gas Metal Arc Welding (GMAW) was chosen as the process used for all specimen preparations because of its wide use for joining heavy section aluminum plate. Procedures and practices used for this work were chosen to correspond as closely as possible to those used in the manufacturing of aluminum combat vehicles. A 2319 filler metal conforming to MIL-E-16053 (AWS A5.10) was chosen based on availability and previous work in the literature.[2-4] The composition range of the 2319 filler alloy used for all 2XXX series welds is shown in Table 1.

The choice of filler metal for welding 2519-T87 was primarily based on Reference 4. It was found that plate composition did not influence the arc characteristics of 2319 electrodes and that the welds were very stable. Since there was little data available for the weldability of 2519-T87, this seemed a reasonable choice since the strength levels of the as-deposited welds were close to the strength of the base plate. Also, the 2319 has a close chemistry to that of the 2519.

2. *Welding Aluminum.* American Welding Society, Miami, Florida, 1972, p. 69.18-32.
3. *Welding Kaiser Aluminum.* Kaiser Aluminum and Chemical Sales, Oakland, California, 2nd ed., 1978, p. 2-28-37.
4. DUDAS, J.H. *Arc Stability and Melting Characteristics of Weld Wire for Use with 2219 Aluminum Alloy Plate.* NASA Contract NAS 8-5132, Task Order M-ME-TLA-AL2, January 1963.

All welding was performed automatically with a Miller Deltaweld 650 constant voltage DC arc welding power source equipped with an Automatic 1D-DW controller. The welding parameters used are listed in Table 2.

Table 2. GENERAL WELDING PROCEDURE FOR 2XXX ALUMINUM ALLOYS

BASE MATERIAL:	2519-T87 OR 2219-T851
WELDING PROCESS:	AUTOMATIC GAS METAL ARC WELDING
EDGE PREPARATION:	EDGES CLEANED WITH ACETONE AND STAINLESS STEEL WIRE BRUSH BETWEEN WELD PASSES
ELECTRODE MATERIAL:	2319
ELECTRODE SIZE:	1/16" DIAMETER
PREHEAT:	NONE
POSTHEAT:	NONE
MAXIMUM INTERPASS TEMPERATURE:	$150^{\circ}F$
POSITION:	FLAT OR HORIZONTAL
CURRENT:	265 AMPS
VOLTAGE:	27 VOLTS
SHIELDING GAS:	100% ARGON
GAS FLOW:	60 CFM
TRAVEL SPEED:	16 IPM

A standard double-vee joint configuration was used to provide weldments from which tension and fatigue specimens were taken. Multiple-pass weldments (4 to 5 passes/groove) were made transverse to the rolling direction of the plate. Mechanical test specimens were machined transverse to the weld axis and located at 1/2 the plate thickness. Figure 1 shows the double-vee joint design and the orientation of the test specimen relative to the weldment. Other joint designs were used for the ballistic shock test weldments as will be discussed later.

Round tensile specimens with a 0.505-inch gauge diameter and a 2-inch gauge length were machined according to MTL SP 77-10 Type TR-1,[5] and met ASTM standards. Specimens were tested using a 20 kip Instron electromechanical tensile tester with a crosshead speed of 0.05 inch/min. A 2-inch, 10% extensometer was used to measure the strain. Tensile tests were performed on 5083-H131, 7039-T64, 2219-T851, and 2519-T87 weldments.

Fatigue testing was undertaken to simulate the action of alternating loads such as would be present under actual vehicle service conditions. Both rotating beam and smooth axial fatigue tests were evaluated. Due to the extensive number of test specimens needed, 2519-T87 was the only alloy tested. This was easily justified due

5. CONWAY, J.A., CURLL, C.H., and SILVA, J.R. *Test Specimens for Mechanical Property Determination.* U.S. Army Materials Technology Laboratory, SP 77-10, p. 9.

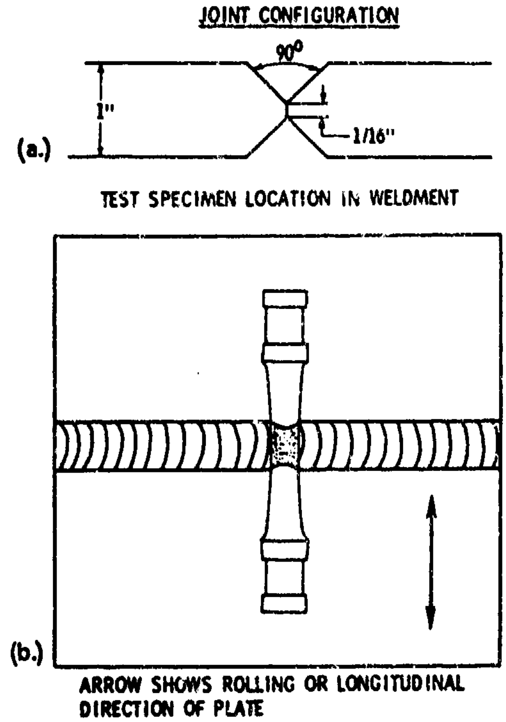

Figure 1. Double-vee joint for mechanical property test weldments and test specimen location in weldment.

to the availability of existing data on the other alloys[6] and the unavailability of data on 2519-T87.

Rotating beam tests were performed with the R.R. Moore technique using a dead weight induced steady load applied as a cantilever with four-point bending yokes while the specimen rotated. The stresses at a point on the surface of the specimen thus experienced a sinusoidal change in value about zero.[7] The smooth axial fatigue tests were performed with equal tensile and compressive stresses (R = -1). Round fatigue specimens were machined according to MTL SP 77-10 Type F2,[8] and met ASTM standards.

Four distinctly different tests were used to evaluate stress corrosion cracking susceptibility: C-ring, cruciform, sandwich, and bent-beam. The entire subject of stress corrosion test specimens for weldments is discussed in ASTM Standard G 58.[9]

The C-ring test specimens were prepared from both the 2519-T87 and 2219-T851 alloy plates as follows. Solid 1-3/8 inch diameter cylindrical bars were machined from 1-1/2 inch thick plate in both the longitudinal and transverse directions. A weld bead was then placed along the surface parallel with the axis of the bar. C-rings were then machined as in Figure 2, in accordance with ASTM G 38, to an

6. HART, R.M. *Alcoa Aluminum Alloys 2219 and 2419.* Aluminum Company of America, 1983.
7. *Handbook of Fatigue Testing.* STP566. American Society of Testing Metals (ASTM), Philadelphia, Pennsylvania. 1974, p. 65.
8. CONWAY, J.A., CURLL, C.H., and SILVA, J.R. *Test Specimens for Mechanical Property Determination.* U.S. Army Materials Technology Laboratory, SP 77-10, p. 35
9. *Standard Practice for the Preparation of Stress Corrosion Test Specimens for Weldments.* ASTM, 58-78, 1978, p. 955-963

outer dimension of 1-1/4 inch and a stress applied ranging from zero up to the yield strength of the base material. The specimens were then immersed for 10 minutes in an aqueous solution of 3.5% sodium chloride followed by a 50-minute drying period in air in accordance with ASTM G 44. This cycle was repeated for 1000 hours or until cracking occurred.

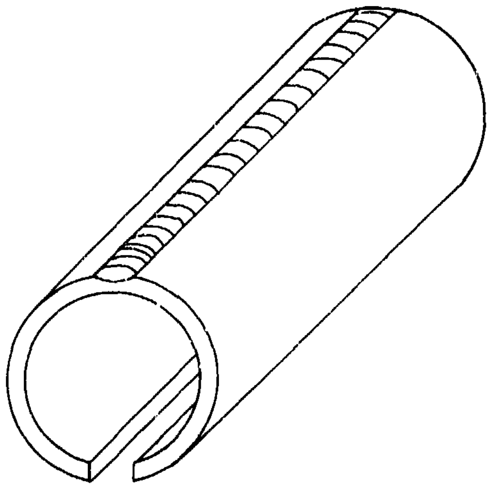

Figure 2. Schematic of the C-ring SCC test specimen.

Cruciform test specimens were made from 2519-T87 and tested in accordance with ASTM G 58. Specimens were subjected to either alternate immersion, as in the case of the C-rings, or a continuous 5% sodium chloride salt fog spray. Testing was performed for 500 hours, and the specimens sectioned at 1-inch intervals and examined for cracking. A schematic of a cruciform weldment is shown in Figure 3.

Bent-beam test specimens were made from 2519-T87 in accordance with ASTM G 39 and a weld bead placed along the specimen width at the center of the beam length. The specimens were stressed in three-point loading, as shown in Figure 4, to 75% of the base metal yield strength. Loaded specimens were subjected to either alternate immersion, as were the C-rings, or a continuous 5% sodium chloride salt fog spray for 500 hours.

Sandwich test specimens consisted of two 4-1/2 inch square plates welded to both sides of a 6-inch-square plate as shown in Figure 5. Once again, specimens were exposed to either alternate immersion or continuous salt fog spray for 500 hours.

The ballistic shock integrity of 2219-T851 and 2519-T87 weldments was tested in accordance with proposed MIL-STD-1946. The shock test in MIL-STD-1946 involves welding two 24 × 18 inch aluminum alloy plates together in the desired configuration and then impacting the welded area (direct hit on the weld for flat plates, and 2 inches from the weld for a corner joint) at least 12 inches from both edges of the plate. A 5-lb aluminum 75-mm M1002A blunt nose projectile is used to strike the plate at a specified critical velocity. The impacted plate is then visually inspected for cracks. A combined length of cracking in excess of 12 inches in the weld, fusion zone, or heat-affected zone is cause for failure of the weldment. Under such circumstances, the weld procedure or joint design must be modified in order to obtain acceptable welds.

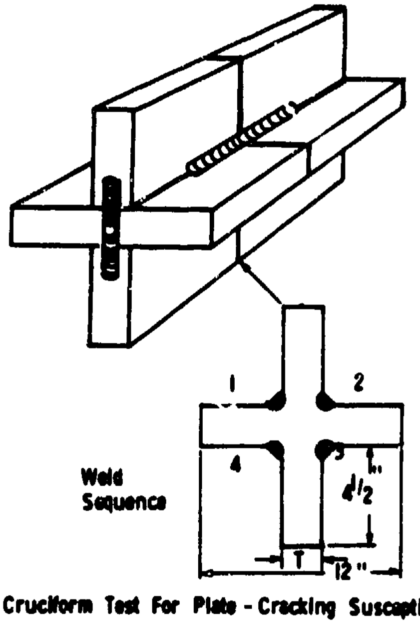

Figure 3. Schematic of cruciform weldment.

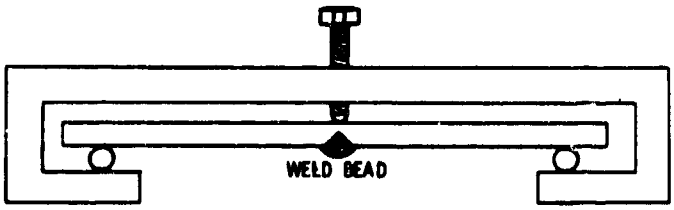

Figure 4. Schematic of bent-beam weldment under three-point loading.

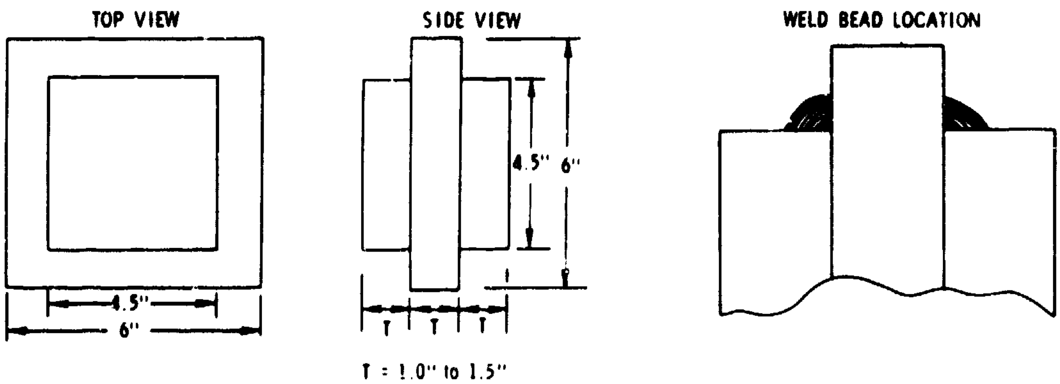

Figure 5. Schematic of sandwich element.

The critical velocity is determined by testing unwelded plates at various projectile velocities until a V_{50} is found. A V_{50} (for the shock test) is the velocity at which there is a 50% chance of the impacted plate exhibiting excessive cracking. The welded plates must withstand a critical velocity equal to 90% of the V_{50} of the unwelded plates. The V_{50}s for several one-inch thick aluminum armor alloys are shown in Table 3. (The value for the 2519-T87 alloy is undergoing further study.) Note that this is not the same V_{50} as would be found when subjecting a plate to a penetrating projectile rather than a blunt nose projectile.

Table 3. V_{50} FOR 12-INCH CRACK LENGTH ON ONE-INCH THICK ALUMINUM ARMOR PLATE*

Aluminum Alloy	V_{50} (ft/sec)
5083-H131	825
7039-T64	775
2219-T851	789
2519-T87	830

*Requires use of 75-mm M1002 aluminum-proof projectile.

Two different weld joint designs were tested in the present study. The corner and offset-vee butt joints used are shown in Figures 6 and 7. The welding parameters used for these joints were the same as those used for the mechanical property specimens shown in Table 2. Weldments were made transverse to the rolling direction with two passes per side for the offset-vee joints and a single pass per side for the corner joints. Each pass was radiographically inspected to ensure weld quality. Two test panels were fabricated for each alloy and joint design. Ballistic shock testing was performed by the Combat Systems Test Activity at Aberdeen Proving Ground in accordance with the current proposed MIL-STD-1946 as it existed in the summer of 1985.

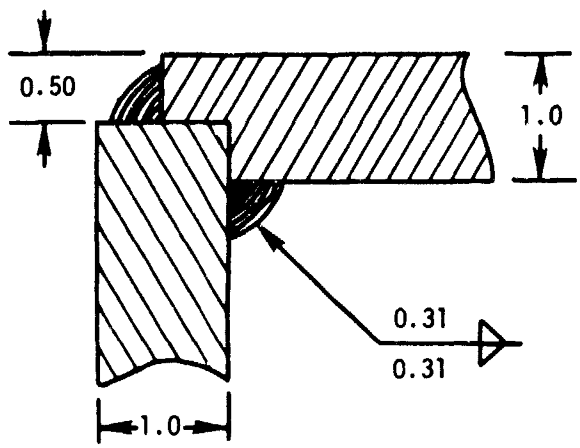

Figure 6. Weld joint design for corner weldments used in ballistic shock tests.

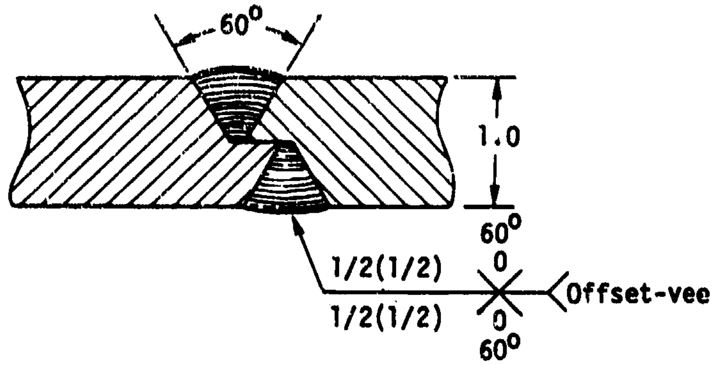

Figure 7. Weld joint design for the offset-vee butt weldments used in ballistic shock tests.

RESULTS AND DISCUSSION

Sound, relatively porous-free welds were achieved using the weld procedure listed in Table 2. Initial problems with lack of fusion were corrected by reducing the root of the double-vee joint to zero, and decreasing the size of the land from 1/8 inch to 1/16 inch. Weld porosity was reduced to an acceptable level by cleaning the plates with acetone prior to welding and using a stainless steel wire brush to remove oxide buildup between weld passes. In addition, hose and torch connections were sealed to prevent air pickup.

Tensile property data obtained on all four aluminum armor alloy weldments are shown in Table 4 along with the calculated weld joint efficiency. It can be seen that the welded tensile strength of the 2519-T87 exceeds that of the other three alloys, indicating that this alloy would have excellent resistance to ballistic penetration. However, the relatively low ductility of both 2XXX aluminum alloys indicates that the resistance to ballistic shock may be poor.

Table 4. AS-WELDED JOINT MECHANICAL PROPERTIES FOR ALUMINUM ARMOR ALLOYS

Alloy	U.T.S. (ksi)	0.2% Y.S. (ksi)	Elong. (%)	Joint Efficiency (%)
5083-H131	41.4	22.3	12.2	78.9
7039-T64	45.0	31.0	11.0	67.0
2219-T851	43.5	26.6	4.9	61.8
2519-T87	45.9	30.4	4.2	64.6

Fundamental physical metallurgy data is currently unavailable for the specific armor alloys being studied, but basic research on other 2XXX and 7XXX series aluminum alloys is available.[10] These results indicate that 7XXX series alloys are less

10. VanHORN, K.R. (Ed.) *Aluminum: Properties, Physical Metallurgy, and Phase Diagrams.* American Society for Metals, v. 1, 1967.

sensitive to property changes as a function of aging, or cooling rate from the solution temperature. This is partially due to the fact that the aluminum-zinc-magnesium (7XXX series) Guinier-Preston zones are smaller (20-35 Å average diameter) and do not increase in size as fast as aluminum-copper (2XXX series) Guinier-Preston zones of 30-50 Å diameter. The 2XXX series zones consist of localized concentrations of copper-rich regions, whereas in the 7XXX series the copper remains in a relatively uniform distribution. Also, no discrete particles of Al-Zn-Mg are found in 7XXX series alloys. Since copper diffuses faster in aluminum than zinc or magnesium, the 2XXX series alloys can overage and embrittle faster than the 7XXX series. The addition of silicon in the 2319 electrode wire can also increase Guinier-Preston zone size close to the fusion line, where failure occurred in the tensile specimens.

The high joint efficiency of the 5083-H131 is due to the fact that this alloy receives its strength from strain hardening, and is not as influenced by the heat of welding as are the three heat treated alloys.

Rotating beam and axial fatigue S-N curves are shown in Figures 8 and 9 for the 2519-T87 alloy. These figures show both the welded and unwelded fatigue strength as a function of cycles tested. The endurance limit is defined as the maximum stress level at which no failure occurs when the specimen is subjected to ten million cycles. Both the rotating beam and smooth axial fatigue data show the fatigue life of the 2519-T87 weldments to be lower than that of the base metal for high stress levels. However, the endurance limit for both welded and unwelded specimens were approximately equal. This endurance limit can be estimated from Figures 8 and 9 to be about 14 to 16 ksi for rotating beam fatigue and 12 to 14 ksi for smooth axial fatigue loading. These values compare favorably with published literature on unwelded 2219 plates.[6]

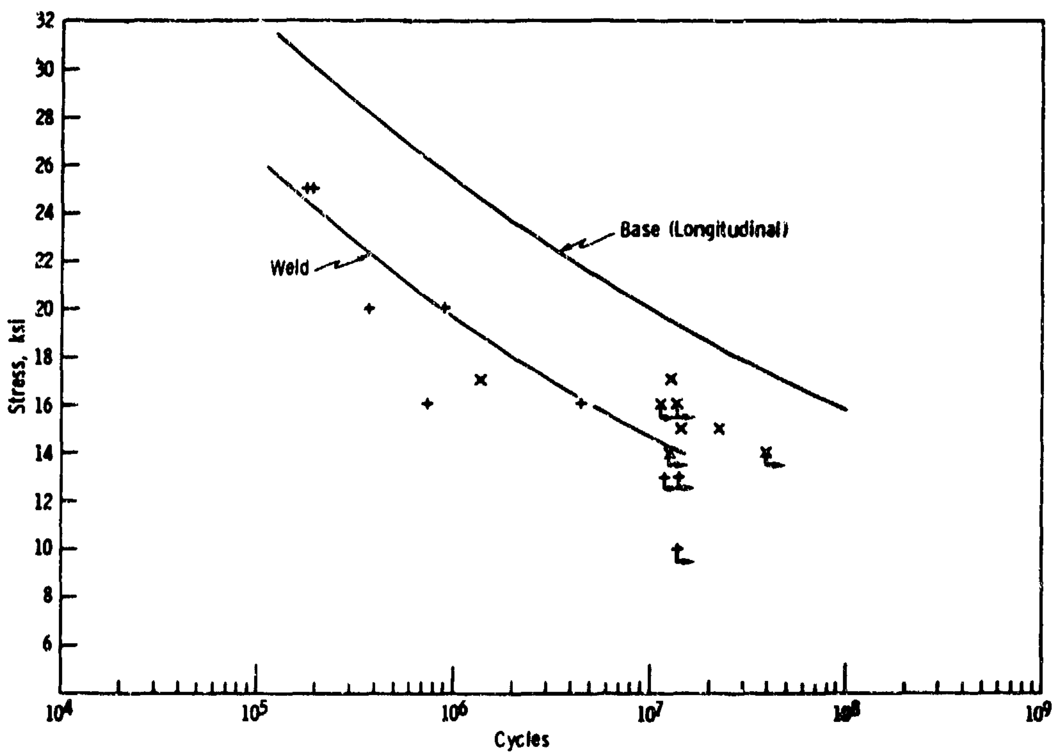

Figure 8. Rotating beam fatigue data for 2519-T87 alloy welds.

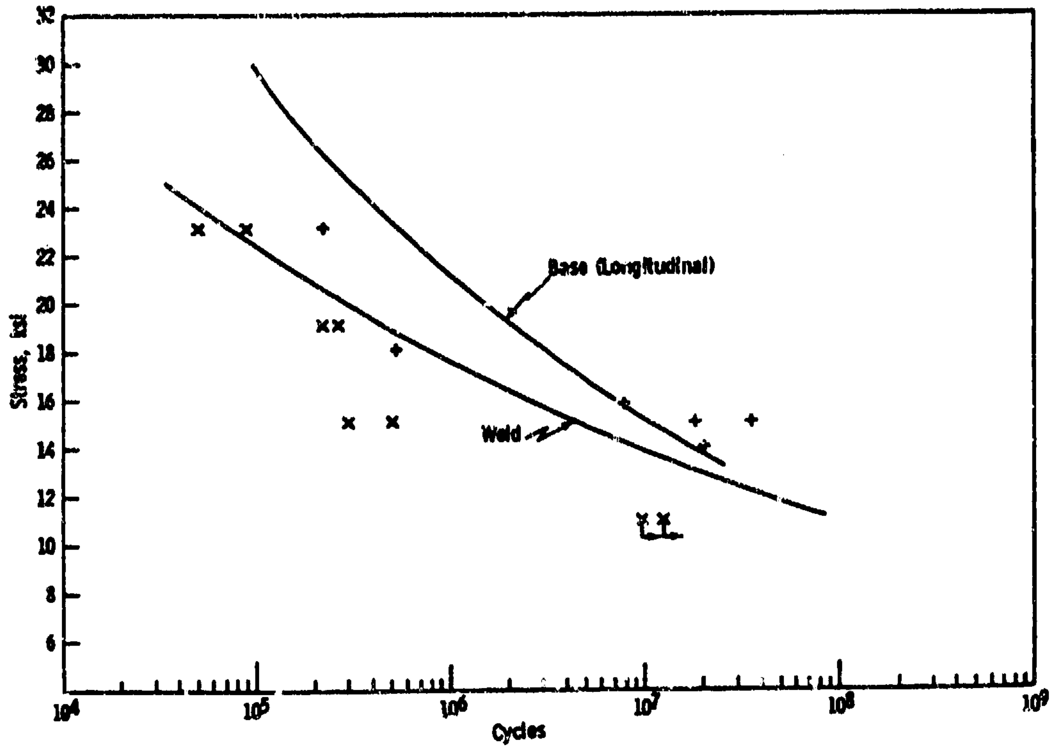

Figure 9. Axial fatigue data for 2519-T87 alloy welds.

In addition to being subjected to alternating loads, aluminum vehicles are also exposed to corrosive environments such as salt water. A corrosive environment coupled with sustained applied and/or residual welding stresses can result in stress corrosion cracking (SCC). Such failures result from the interaction of corrosive attack and sustained tensile stress in the presence of a notch. It is characterized by selective corrosion along a relatively continuous path, such as a grain boundary. It is most likely to occur when a sustained surface tensile stress acts approximately perpendicular to the affected grain boundary. In weldments, this generally means that SCC occurs in the HAZ where grain boundary segregation and high residual tensile stresses are at their worst.

In general, SCC has not been a problem with the 2XXX series aluminum alloys.[11] However, the increased use of higher strength aluminum alloys in larger and more sophisticated structures has resulted in increased residual welding stresses and locked in assembly stresses.[12] For this reason, and the fact that no data exists for SCC of 2519-T87, four different tests were used in this study for a complete evaluation.

Results of the C-ring SCC test are shown in Table 5. This table lists the time-to-failure in hours (or 1000 hours if no failure occurred) of C-rings from both 2519-T87 and 2219-T851 stressed with the weld on either the longitudinal or short transverse face of the sample. Cracking occurred for both 2XXX series alloys only

11. MEISTER, R.P, and MARTIN, D.C. *Welding of Aluminum and Aluminum Alloys.* Report 236, Defense Metals Information Center (DMIC), Columbia, Ohio, April 1967.
12. SHUMAKER, M.B., KELSEY, R.A., SPROWLS, D.O., and WILLIAMSON, J.G. *Evaluation of Various Techniques for Stress Corrosion Testing Welded Aluminum Alloys.* ASTM, Stress Corrosion Testing Symposium, 1966, p. 7-8.

Table 5. C-RING SALT WATER STRESS CORROSION CRACKING RESULTS
(Time-to-Failure in Hours)

Applied Stress (ksi)	2519-T87 (L)	2519-T87 (ST)	2219-T851 (L)	2219-T851 (ST)
00	1000	1000	1000	1000
05	1000	1000	1000	1000
10	1000	1000	1000	1000
15	1000	1000	1000	1000
20	1000	90	1000	280
25	1000	90	1000	280
30	1000	90	1000	280
35	1000	90	1000	280

L - Weld bead on longitudinal face

ST - Weld bead on short transverse face

in the short transverse direction for an applied stress of 20 ksi or above. This applied load is in addition to the residual welding stress so that the specimens failed under a load probably well in excess of the yield strength. Residual welding stresses are typically about equal to the yield stress of the weld metal.

Of the four SCC tests selected for this study, the cruciform test exposes the weld zone to the highest degree of restraint and residual stresses. This test is especially useful in evaluating the underbead SCC tendency in the HAZ. Of the ten 2519-T87 cruciforms tested, only one weldment developed a crack after the 500-hour testing time. This one crack occurred in the HAZ of a weld which had been erroneously placed off center. Also, since the crack occurred in the second weld instead of the fourth (which is subject to the highest restraint and stress), this one crack was discounted.

The bent-beam test measures SCC tendency in the weld, fusion line, and HAZ due to residual stress and the stress due to the elastic strain of bending. No failures occurred after 500 hours in five bent-beam 2519-T87 specimens loaded to approximately 75% of the base metal yield strength.

The sandwich test subjects the middle plate to tensile stresses along the short transverse axis which is generally the most susceptible to SCC. The 7039-T64 alloy cracked after only 100 hours of testing, whereas the seven 2519-T87 sandwich specimens showed no SCC failures after 500 hours of testing. This result is significant because the short transverse direction is typically where SCC is at its worst.

A summary of the SCC results is presented in Table 6 for the cruciform, bent-beam, and sandwich tests on 2519-T87. Results show that 2519-T87 weldments are very resistant to SCC. Caution must be exercised, however, when high applied loads in addition to residual stresses are present in the weld HAZ in the short transverse direction, as occurred in the C-ring specimens that failed.

Most manufacturers realize the potential for SCC whenever residual weld stresses act perpendicular to the short transverse direction of an exposed plate edge. This problem can generally be eliminated by redesigning the joint location or "buttering" over the exposed edge with weld metal. However, these "solutions" add unwanted cost and risk.

Table 6. STRESS CORROSION CRACKING TEST RESULTS FOR 2519-T87 ALLOY WELDMENTS

Specimen Type	Test Medium	No. of Specimens Tested	No. of Specimens With Weldment Cracks
Cruciform	5% NaCl Spray	3	0
	3.5% NaCl Bath	7	1
Sandwich	5% NaCl Spray	5	0
	3.5% NaCl Bath	2	0
Bent-Beam	5% NaCl Spray	2	0
	3.5% NaCl Bath	3	0

Ballistic shock testing was performed on both 2519-T87 and 2219-T851 weldments in accordance with proposed MIL-STD-1946 which was discussed earlier. The corner joints were impacted on the outside face. One of the corner joints was impacted on the face with the 1/2 × 1/2 inch cutout, which is referred to as the "weak side." The other corner joint of each alloy was impacted on the "strong side," which is the outside face perpendicular to the weak side. The test results are tabulated in Table 7.

Table 7. RESULTS OF MIL-STD-1946 BALLISTIC SHOCK TEST ON ALUMINUM WELDMENTS (75-mm M1002A Proof Projectile)

Alloy	Impact Velocity (ft/sec) and Results*: Offset-Vee Joint	Corner Joint
2219-T851	710 Failure	710 Failure
	721 Failure	838 Failure
2519-T87	748 Failure	751 Failure
	762 Failure	773 Failure

* Failure defined as cracking in excess of 12" total length

All of the 2XXX series aluminum armor weldments failed ballistic testing. MIL-STD-1946 requires that weldments withstand 90% of the unwelded V_{50}'s shock. The 710 ft/sec failure of the 2219-T851 was exactly 90% of the unwelded V_{50}, and the 748 ft/sec failure of the 2519-T87 was also exactly 90% of the unwelded base plate V_{50} (see Table 3 for unwelded V_{50}s). Unfortunately, the velocity at which 2XXX series alloys would have passed the 12-inch crack criterion was not established. Thus the degree, or seriousness, of the ballistic failures was not determined since most of the welds were impacted at a higher velocity than required.

The offset-vee butt welds of both alloys fractured along the fusion line with crack lengths ranging from 15 to 18 inches. Figure 10 shows an example of the impact side of one of the four butt welds tested. Figure 11 is the reverse side of the same place showing the fracture and opening. Since no experimental data exists for the crack length as a function of velocity, it is not known if these plates would have passed (i.e., experienced 11 inches of crack rather than 14) had the impact velocity been slightly less.

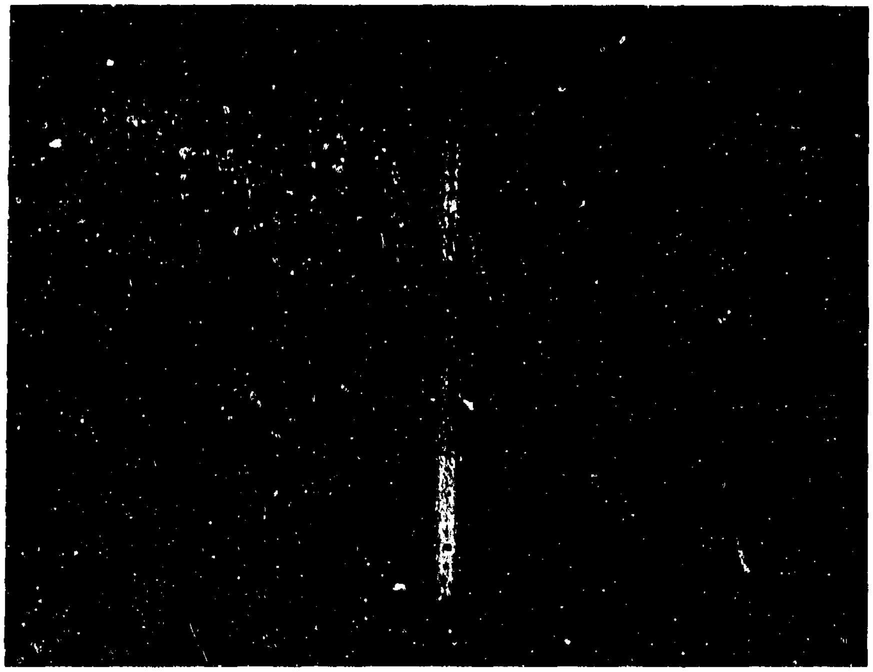

Figure 10. Impact side of a butt welded 2219-T851 MIL-STD-1946 ballistic weldment.

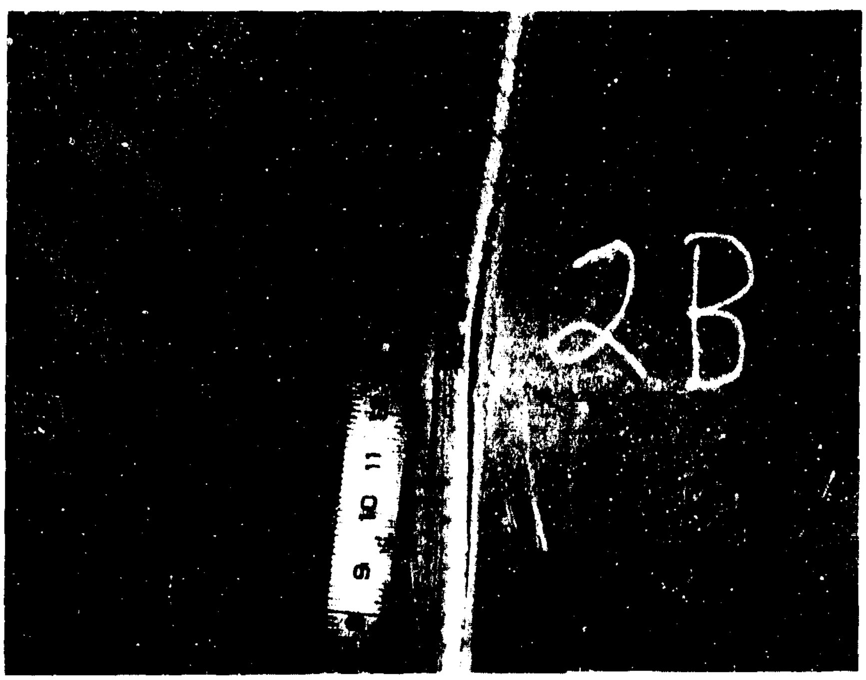

Figure 11. Closeup of reverse side of Figure 10 showing crack in fusion zone.

The corner joint failures ranged from complete separation of the two plates to only 14 inches of cracking. Figures 12 and 13 show a 2519-T87 failure which fractured in both the weld and base metal at a velocity in excess of the critical

Figure 12. Corner weldment of 2519-T87 impacted in excess of the critical cracking velocity.

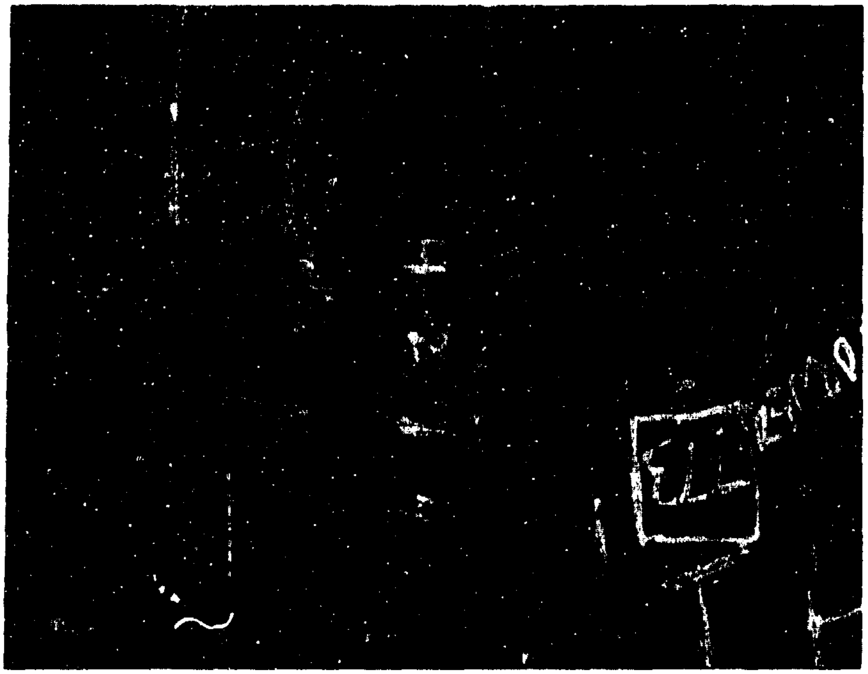

Figure 13. Closeup of Figure 12 showing failure in weld area and base metal.

cracking velocity. Figures 14 and 15 show a 2219-T851 failure which occurred at the critical cracking velocity. This was the only crack which occurred in the weld metal itself rather than the fusion line or base metal.

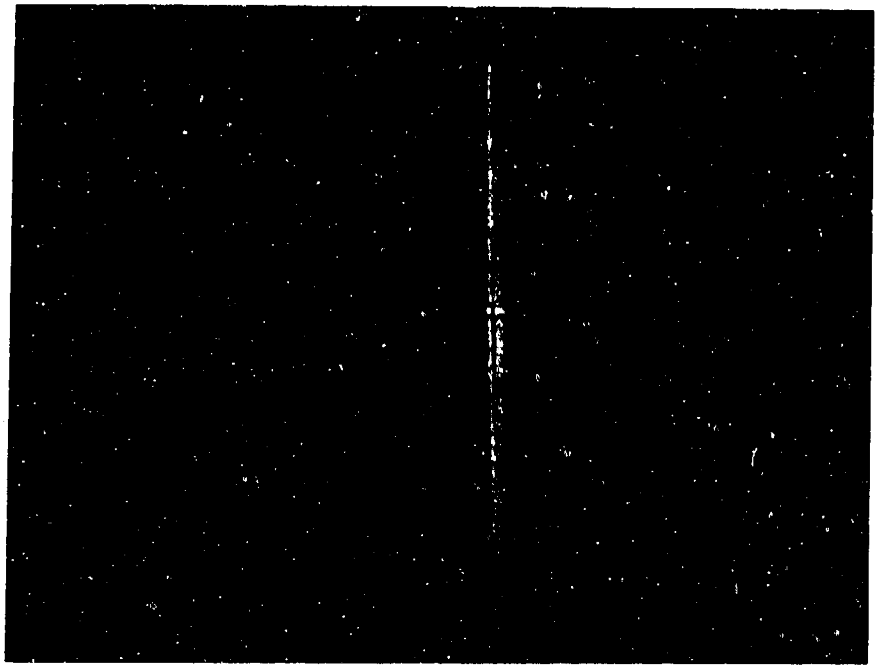

Figure 14. Corner weldment of 2219-T851 impacted at the critical cracking velocity.

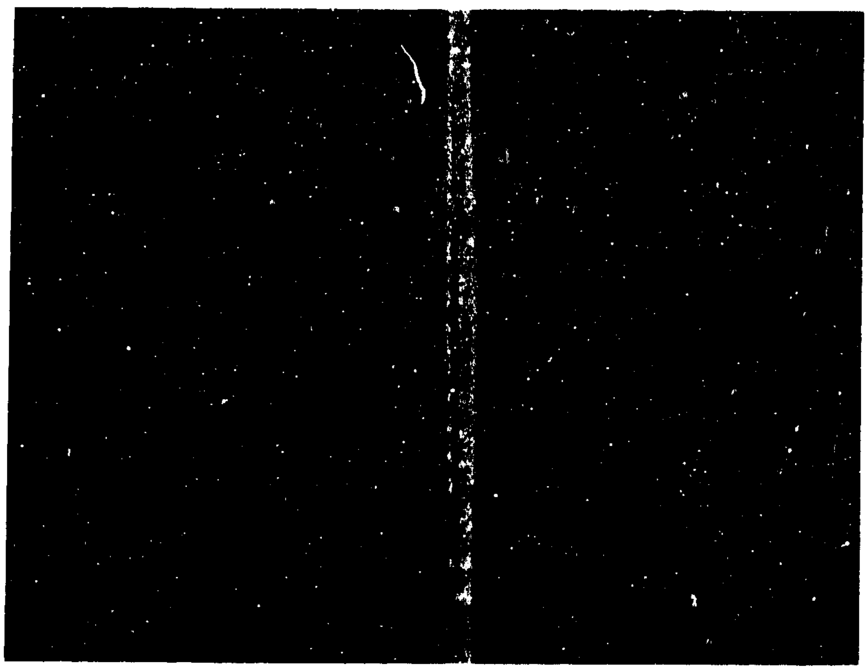

Figure 15. Closeup of Figure 14 showing failure in the weld metal.

The corner joint weld sizes were undoubtedly too small for the thickness plates being tested. This contributed to the failures, but was not the only explanation as is evidenced by the failure of the butt welds as well. This will be examined in the next series of tests which will have larger fillet sizes.

Previous ballistic shock testing experience also indicates that the vee groove included angle may need to be increased. This reduces the sharp contour at the root of the weld, allows better access to the root, and possibly increases penetration. Increasing the angle will necessitate adding more weld passes to fill in the groove. This may be a benefit by distributing the weld region over a larger area.

It may well be that the low ductility of the 2XXX series weldments is a fundamental problem of these alloys. Reducing the silicon content of the filler metal or altering the chemistry of the base metal may be the only solution to the problem if weld process modification (i.e., higher heat input or use of stringer beads) cannot be shown to increase ductility.

On the other hand, a more extensive ballistic test matrix may prove that the 2XXX series can withstand slightly lower than 90% of the unwelded V_{50}. If these critical velocities are higher than those of the 5083-H131 or 7039-T64, then ductility would no longer be considered such a problem, and strong consideration could be given for use of these alloys in Army vehicles.

FUTURE WORK

Work is now underway on corner joints with more weld area, and other joint designs are being considered. Increasing the ductility of 2519-T87 weldments is also being investigated.

Other work will concentrate on extending the data on critical cracking velocities of 2519-T87 weldments, the influence of minor weld discontinuities on ballistic test results, and understanding ballistic shock test variables which can influence cracking levels.

Another major issue to be addressed before a 2XXX series alloy can be seriously considered for use in Army vehicles is weldability to dissimilar aluminum alloys. In particular, 5083-H131 is often used for attachments on a vehicle. Also, the weldability to 355 and 356 cast aluminum must be considered.

SUMMARY

Sound, porous-free welds on aluminum armor alloys 2519-T87 and 2219-T851 can be produced using the Gas Metal Arc Welding (GMAW) procedure developed in this study.

Weld tensile strength (ultimate and yield) of the 2519-T87 alloy equals or exceeds that of 2219-T851, 5083-H131, and 7039-T64 aluminum armor alloys; however, elongation of the 2XXX series alloy welds examined (without post heat treatment) is significantly lower than that of the 5083 or 7039 alloys.

The endurance limit of 2519-T87 weldments was approximately equal to the unwelded base metal. This endurance limit is 14 to 16 ksi for rotating beam, and 12 to 14 ksi for smooth axial fatigue loading.

The 2519-T87 weldments generally show no susceptibility to stress corrosion cracking in a salt water environment for the testing times evaluated. Problems can arise, however, when weld residual stresses act perpendicular to an exposed short transverse edge.

Preliminary trials on ballistic shock loading of the 2XXX series alloys show potential problems with weld joint toughness. These issues will be addressed in future research.

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Also, many thanks to the engineers at FMC (the maker of the Bradley Fighting Vehicle and other light combat vehicles) for their part in developing 2519-T87 for use as an armor material. Special thanks to Ken Keck for his informative comments on ballistic shock testing and material properties needed by aluminum fighting vehicles.

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WELDABILITY OF 2219-T851 AND 2519-T87 ALUMINUM ARMOR ALLOYS FOR USE IN ARMY VEHICLE SYSTEMS
Thomas D. Wolfe and Steven A. Gedeon

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